Experimental Top Quark Physics

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Outline:

- Introduction
- Top Quark Production and Detection
- $\sigma_{t\bar{t}}$ Measurements
- M_{top} Measurements
- V_{tb}
- Conclusions

Introduction

There are good reasons to expect new physics beyond the Standard Model

Top quark physics is a good place to look.

- **Measurements of Standard Model Parameters like M_{Top}**

- **Direct Searches for new objects or new phenomena**

- **Top physics is less than three years old**

A Short History of a Long Search

- 1977-1994: **A fine collection of null results**

- April, 1994: **First Evidence**
  - **Phys. Rev. D50, 2966 (1994) CDF**
  - 15 events on a background of 6.0
  - 2.8 σ excess
  - $M_{top} \ = \ 174 \pm 17 \ GeV/c^2$
  - $\sigma_{t\bar{t}} \ = \ 13.9^{+6.1}_{-4.8} \ pb$

- February, 1995: **Confirmation**
  - **PRL 74, 2626 (1995) CDF**
  - 4.8 σ excess
  - $M_{top} \ = \ 176 \pm 8(stat) \pm 10(syst) \ GeV/c^2$
  - $\sigma_{t\bar{t}} \ = \ 6.8^{+3.6}_{-2.4} \ pb$
  - **PRL 74, 2632 (1995) D0**
  - 4.6 σ excess
  - $M_{top} \ = \ 199^{+19}_{-21}(stat)^{+14}_{-21}(syst) \ GeV/c^2$
  - $\sigma_{t\bar{t}} \ = \ 6.4 \pm 2.2 \ pb$

Top Production at the Tevatron

Top quarks are predominantly produced in pairs by the process $p\bar{p} \to t\bar{t}$.

The lowest order production diagrams are:

NLO Calculations:

- Laenen, Smith & van Neerven, Phys. Lett. **B221** 254 (1994)
- Berger & Contopanagos, hep-ph/9606421
- S. Catani, M.L. Magano, P. Nason, & L. Trentadue, CERN-TH/96-21 and CERN-TH/96-86

In Tevatron RunI, For both D0 and CDF:

- $\int Ldt$ exceeded 100 pb^{-1}
- over 5×10^{12} $p\bar{p}$ collisions
- **$\approx$ 500 $t\bar{t}$ pairs produced.**

$$\frac{\sigma_{\mathbf{t\bar{t}}}}{\sigma_{\mathbf{inel}}} \sim \mathbf{10^{-9}}, \qquad \frac{\sigma_{\mathbf{t\bar{t}}}}{\sigma_{\mathbf{W}}} \sim \mathbf{10^{-3}}$$

- Single top production through Wg fusion and W^* production is about 20% of this rate, and has not yet been observed.

Top Quark Decay Signatures

Within the Standard Model,

$$p\bar{p} \to t\bar{t} \to W^+b, \quad W^-\bar{b}$$

We categorize top decays by how the two W bosons decay. The W's can decay to quarks ($u\bar{d}$ or $c\bar{s}$), or to leptons ($e\ \nu$, $\mu\ \nu$, or $\tau\ \nu$). The quarks will fragment into jets. So $t\bar{t}$ events are grouped into obvious categories:

Channel	Fraction	%
Dilepton $\quad e^\pm\mu^\mp,\ e^\pm e^\mp,\ \mu^\pm\mu^\mp\ + X$	$\frac{4}{81}$	5%
Lepton $\quad (e^\pm$ or $\mu^\pm) + jets$	$\frac{24}{81}$	30%
All Hadronic	$\frac{36}{81}$	44%

Dilepton Channels

Signature:

- Two isolated high P_T leptons (e or μ)
- $\not\!\!E_{\mathrm{T}}$
- 2 or more jets

Dominant Backgrounds:

- WW
- $Z \rightarrow \tau\tau$
- Fake leptons
- Drell Yan

Features:

- Good Signal-to-background ratio but low statistics
- Not ideal for top mass determination (two neutrinos)

Lepton + Jets Channels

Signature:

- One isolated high P_T lepton (e or μ)
- $\not{E}_{\mathrm{T}}$
- 4 or more jets, 2 of which are from b-quarks

Dominant Backgrounds:

- $p\bar{p} \to W + jets$

- QCD background (Fake leptons)

Features:

- **Need to further suppress backgrounds either with:**
  - **Topological/kinematic requirements:**
    - Aplanarity
    - $H_T = \Sigma E_t^{jets}$
  - **b-jet tagging**
    - Displaced vertex b tag (**SVX Tag**) CDF
    - Low energy leptons from semileptonic b decay (**Soft Lepton b Tags**)
- Better sample for top mass determination (only one neutrino)

All Hadronic Channel

Signature:

- 6 or more jets, 2 of which are from b-quarks
- not all 6 jets are always observed

Dominant Backgrounds:

- QCD multijet production

Features:

- Signal-to-background is $\sim \frac{1}{30}$ before additional topological/kinematic requirements or b-tagging
- If background can be controlled, top mass determination possible (no neutrinos)

$\sigma_{t\bar{t}}$ Measurements

Outline

- D0 Dilepton Channel
- D0 Lepton+jets Channel
  - ∗ Topological Analysis
  - ∗ Low Momentum Muon b-Tag
- CDF Lepton+Jets Channel
- CDF Dilepton Channel

Other Top Cross Section Measurements:

- D0 All Hadronic Channel
- CDF All Hadronic Channel
- CDF b-tagged Dilepton Channel
- CDF τ-Dilepton Channel

Goal: Determine the top cross section

- **as accurately as possible**
- **in as many different decay channels as possible as a check of top decay.**

CDF Lepton+Jet Event Selection

- **1 High E_t Lepton (e or μ)**
  - E_t >20 GeV
  - Central ($|\eta| < 1.1$)
  - Isolated
- $\not{E}_T > \ 20\ GeV$
- **3 Jets with $E_T > 15\ GeV$ and $|\eta| < 2.0$**
- **Require at least 1 jet to be b-tagged**
  Either
  - Displaced Vertex SVX b tag
  - Soft Lepton (SLT) b tag

Summary of CDF Lepton+Jets Results

Total Integrated Luminosity = 109 pb^{-1}

SVX b-Tagging Results

	Total Background Events	Observed Events (Tags)
W+1 Jet	69 ± 1	70 (70)
W+2 Jet	29.1 ± 3.7	45 (51)
W+3 Jet	6.7 ± 0.9	18 (24)
W+$\geq$ 4 Jet	2.6 ± 0.5	16 (18)

Soft Lepton b-Tagging Results

	Total Background Events	Observed Events (Tags)
W+1 Jet	273 ± 35	70 (70)
W+2 Jet	79 ± 10	45 (51)
W+3 Jet	17.4 ± 2.8	25 (27)
W+$\geq$ 4 Jet	7.8 ± 1.0	15 (17)

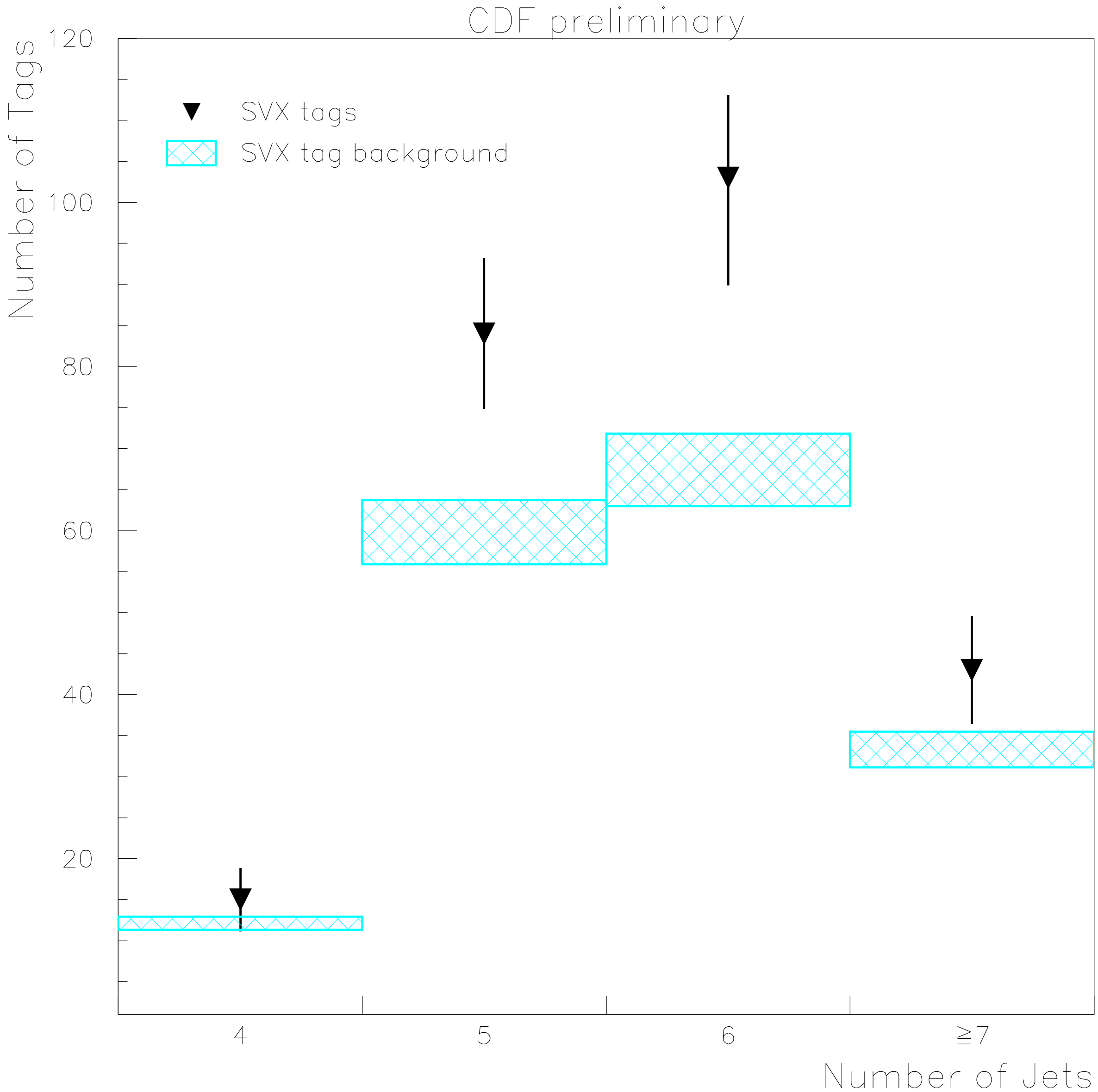
CDF All Hadronic Event Selection

From events that passed the multijet trigger (clustered $\Sigma E_t >$ 125 GeV), we further require:

- $N_{jet} \geq 5$
- $\Delta R_{min} \geq 0.5$
- $\Sigma E_t \geq 300\ GeV$
- $\Sigma E_t/\sqrt{\hat{s}} \geq 0.75$
- Selection in the Aplanarity-ΣE_t plane.

$$A + 0.0025 \times \sum_{3}^{N} E_T \ \geq \ 0.54$$

- **$\geq$ 1 SVX b-tagged jet**



CDF preliminary
SVX tags
SVX tag background
Number of Tags
120
100
80
60
40
20
4
5
6
≥7
Number of Jets

CDF Dilepton Event Selection

- **2 High E_t Leptons (e or μ)**
  - E_t >20 GeV
  - Central ($|\eta| < 1.1$)
  - Oppositely charged
- **At least 1 lepton must be Isolated:**
  - $I = \frac{E_T^{0.4} - E_T^{Lep}}{E_T^{Lep}}$
  - $I_{cal} < 0.1$
  - $I_{track} < 0.1$
- Dilepton Invariant mass not in Z region $75 - 105\ GeV/c^2$
- $\not\!\!E_T > 25\ GeV$
- If $\not\!\!E_T < 50$ GeV, require $\Delta\phi(\not\!\!E_T - l\ or\ jet) > 20^\circ$
- 2 Jets with $E_T > 10\ GeV$

Summary of CDF Dilepton Results

Total Integrated Luminosity = 109 pb^{-1}

Requirement	ee	$\mu\mu$	$e\mu$
Lepton ID	2857	3452	68
Opp. Charge	2847	3444	55
Isolation	2798	3457	49
Invariant Mass	316	375	49
$\not\!E_T$	6	7	16
2 Jets	**1**	**2**	**7**

CDF τ-Dilepton Event Selection

Look for *hadronic* tau decay to 1 or 3 prong. Require:

- 1 primary lepton (e or μ)
- ≥ 2 jets
- $\not\!\!E_{\mathrm{T}}$ significance greater than 3 σ
- $H_T = E_T^l + P_T^\tau + \not\!\!E_{\mathrm{T}} + \Sigma E_T^{jets} \geq 180\ GeV$
- 1 hadronic τ candidate

  τ identification via:

  - Require 1 or 3 tracks in a 10° cone
  - E/P consistent with τ Monte Carlo
  - e and μ removal
  - Track Isolation
  - $P_T^\tau > 15\ GeV/c$

Observe 4 Events, expect 2.0 ± 0.4 from background processes.

Of the 4 Events, 3 are b tagged with displaced Vertex or Soft Lepton b tag

Summary of CDF $\sigma_{t\bar{t}}$ Results

Channel	acc.×Br. (%)	Background	N_{obs}	$\sigma_{t\bar{t}}(pb)$
SVX	3.5 ± 0.7	8.0 ±1.4	34	$6.8^{+2.3}_{-1.8}$
SLT	1.7 ± 0.3	24.3 ±3.5	40	$8.0^{+4.4}_{-3.6}$
DIL	0.77 ± 0.08	2.1 ±0.4	10	$9.3^{+4.4}_{-3.4}$
τ-DIL	0.119 ± 0.014	1.96 ±0.35	4	$15.6^{+18.6*}_{-13.2}$
b-Tag DIL	0.51 ± 0.03	1.4 ±0.3	4	$4.6^{+4.4}_{-3.1}$
All Had.	4.7 ± 1.6	137.1 ± 11.3	192	$10.7^{+7.6}_{-4.0}$

*Statistical uncertainty only.

Combined Dilepton, SVX, Soft Lepton *b*-Tagged Cross Section:

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{7.5^{+1.9}_{-1.6}\ pb}$$

Top Mass Measurements

Outline

- Determining the Top Mass in the Lepton+Jets Channel
  - **D0**
  - **CDF**
- Summary of other M_{top} Measurements
  - **CDF Lepton+Jets Analysis Using Jet Charge and Jet Tagging Probability**
  - D0 Dilepton Top Mass
  - **CDF Dilepton Top Mass**
  - CDF Top Mass Measurement in the All Hadronic Channel

Goal: Determine the top mass

- **as accurately as possible**
- **in as many different ways as possible**

as a check of the methods, systematics, etc.

Measuring the Top Mass In the Lepton+Jets Channel

Event Fitting

In the sample of events with a W and ≥ 4 jets, one can make a one-to-one mapping of jets to quarks (using the 4 highest E_T jets) assuming the decay chain:

$$
\begin{gathered}
p\bar{p} \longrightarrow t_1 + t_2 + X \\
t_1 \longrightarrow b_1 + W_1 \\
t_2 \longrightarrow b_2 + W_2 \\
W_1 \longrightarrow \ell + \nu \\
W_2 \longrightarrow j_1 + j_2
\end{gathered}
$$

- We impose:
  - $M_{t1} = M_{t2}$
  - $m(j_1 j_2) = m(\ell\nu) = M_W$, the Measured W mass
- Energy and momentum conservation plus constraints give 20 equations with 18 unknowns $\Rightarrow$ **2-C constrained fit**.

- If a b-tagged jet is only used as a b, with 1 b tag there are 12 possible combinations
- The χ^2 for the specific combination is used to choose the best mass for the event.
- **With a b tag, the lowest χ^2 combination is only the correct one $\sim 35\%$ of the time**
- **Wrong combinations give a broader mass distribution but are centered at the correct mass.**
- With a sample of masses so determined, use log-likelihood method to fit data to sum of $t\bar{t}$ Monte Carlo + background.
- Vary M_{top}, refit, at each top mass saving the minimum log-likelihood.
- Fit the minimum log-likelihood distribution vs. Top mass to measure M_{top} and $\sigma_{M_{Top}}$.

D0 Lepton+Jet Top Mass Determination

- Event selection same as for the cross section measurement except also require:
  - ≥ 4 Jets in the soft μ b-tagged Sample
  - $|\eta_W| < 2.0$ in the non-tagged sample
- Yields:

8 Tagged Events, 85 non-Tagged Events

Plan:

- Use 4 kinematic variables to separate top from background
- Show Monte Carlo is accurate for these variables using control samples in data
- Combine the 4 variables into 1 **Discriminant D** which separates top from background
- D is almost completely independent of the top mass
- **Fit data in two dimensions: D and M_{top}**

CDF Standard Method on the Lepton+Jets Sample

This analysis technique is largely unchanged since its first use in 1994: **Phys. Rev. D 50, 2966 (1994) CDF**

Require:

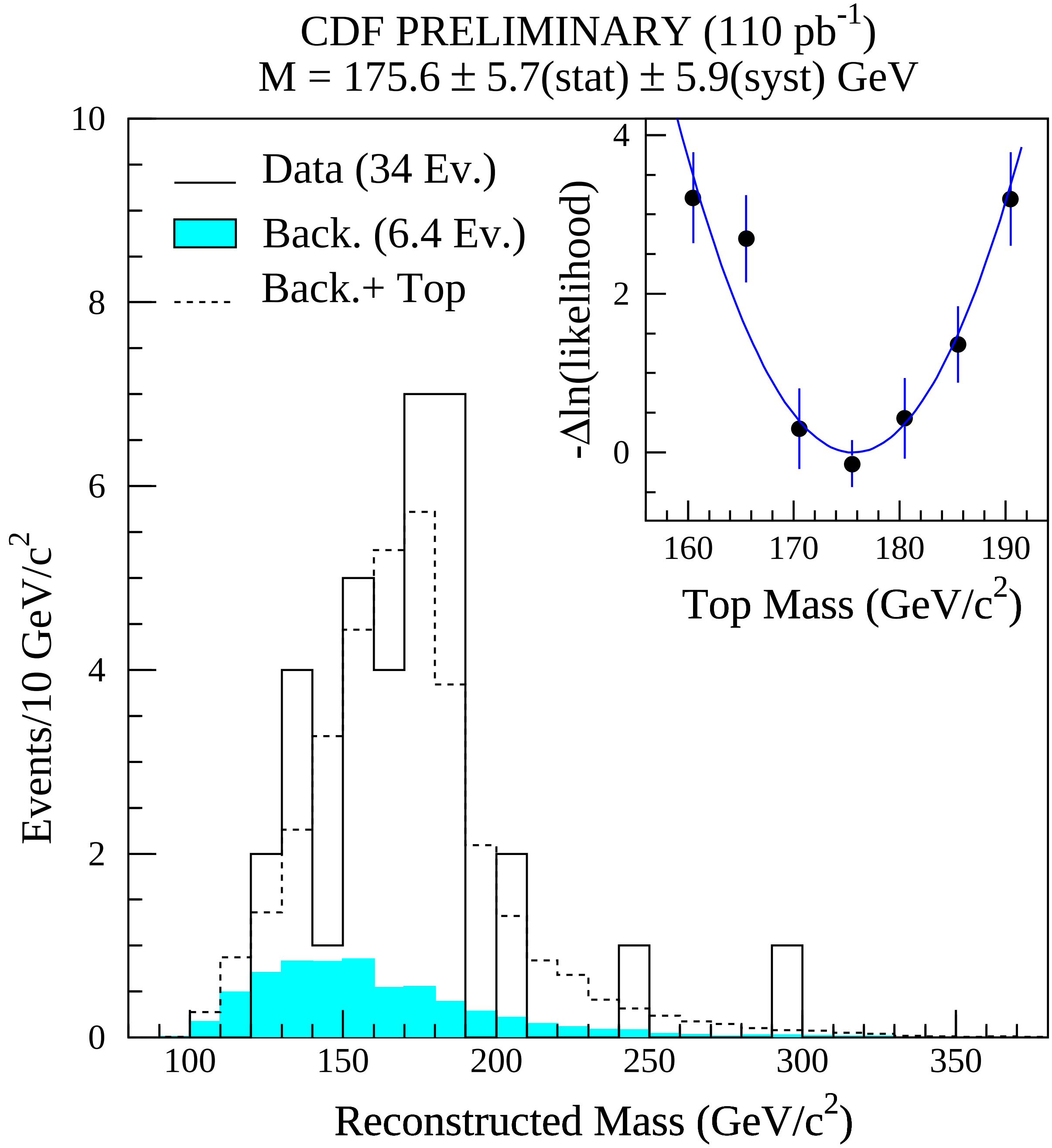
- 3 Jets with $E_T > 15\ GeV$ and $|\eta| < 2.0$
- Loose 4^{th} Jet Requirement: $E_T > 8\ GeV$ and $|\eta| < 2.4$
- Require at least 1 b tagged Jet (either Displaced Vertex or Soft Lepton)
- **34 events** pass selection criteria
- Events treated as a single sample
- Estimated non-$t\bar{t}$ background $6.4^{+2.0}_{-1.5}$ events

- **Re-evaluation of systematic uncertainties:**

CDF Preliminary

Systematic Uncertainties for the Standard Method

Systematic	Previous Value GeV/c^2	New Value GeV/c^2
Soft Gluon + Jet E_T Scale	3.6	3.8
Different Generators	0.9	1.6
Hard Gluon Effects	3.6	3.6
Kinematic and Likelihood Fitting Methods	–	2.0
Fit Configuration (now included above)	2.5	–
Likelihood Method (now included above)	2.0	–
b-tagging Bias	2.3	0.3
Background Spectrum	1.6	0.7
Monte Carlo Statistics	2.3	0.9
Total	**7.1**	**5.9**


CDF PRELIMINARY (110 pb-1)
M = 175.6 ± 5.7(stat) ± 5.9(syst) GeV
Data (34 Ev.)
Back. (6.4 Ev.)
Back.+ Top
Events/10 GeV/c2
Reconstructed Mass (GeV/c2)
-Δln(likelihood)
Top Mass (GeV/c2)
0
2
4
6
8
10
100
150
200
250
300
350
160
170
180
190

The Optimized Method on the Lepton+Jets Sample

The Standard CDF Mass Analysis does not make optimal use of the data:

- It combines SVX and Soft Lepton b-tagged events in the same sample, **even though signal-to-background ratios are very different (2.6/1 vs. 0.6/1)**
- Does not treat separately double b-tagged events, which have even better signal-to-background
- Does not use the untagged events

The optimized method:

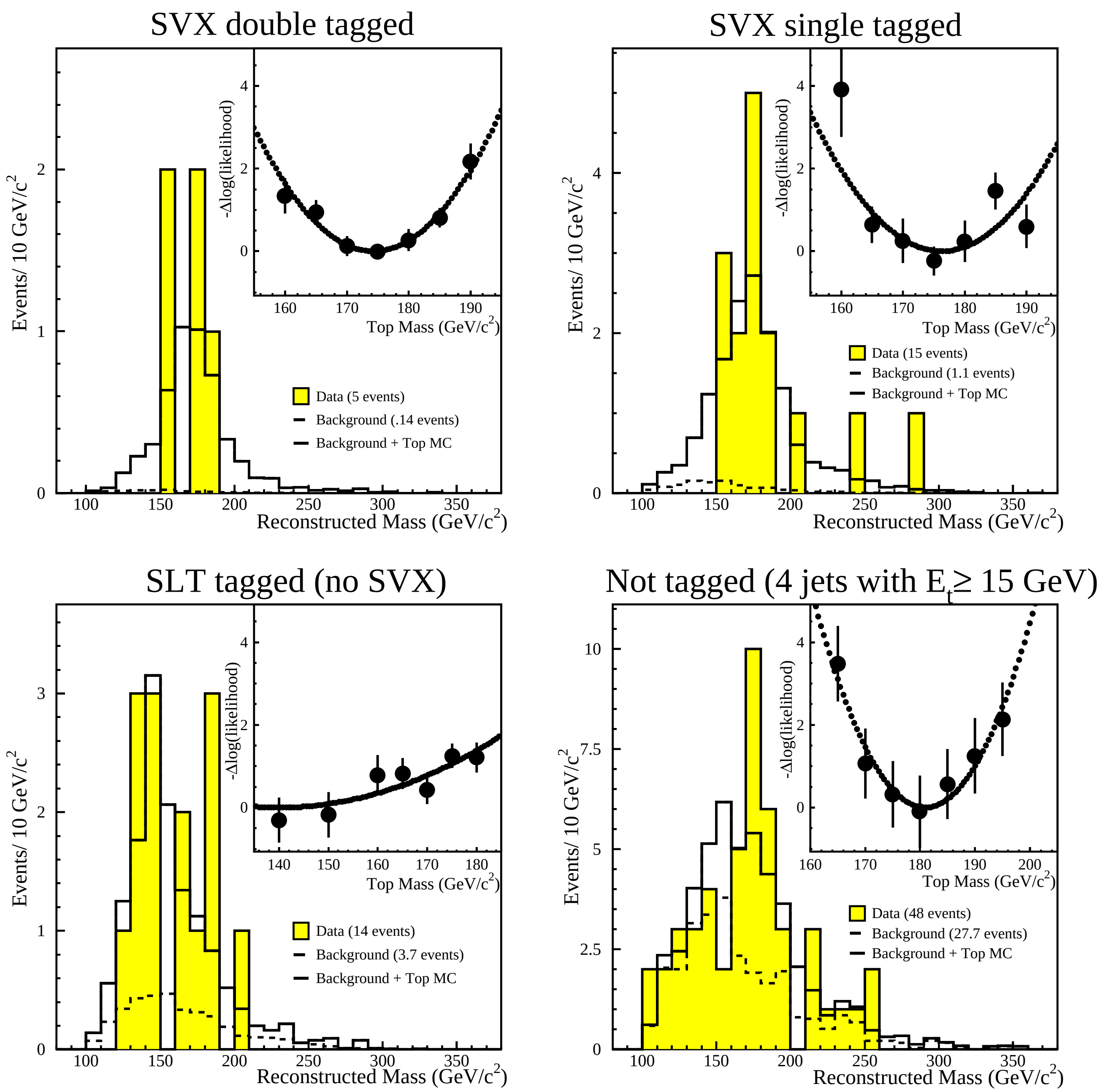
- **Divide data into 4 exclusive sub-samples:**
  - **1** SVX single tagged events
  - **2** SVX double tagged events
  - **3** SLT but not SVX events
  - **4** non-tagged events
- Increase signal-to-background ratio in the non-tagged events by requiring **all 4 jets to have $\mathbf{E_T > 15\ GeV/c^2}$**
- **Fit each sample to Monte Carlo** of top signal and Background, vary M_{top}
- **Extract likelihood vs. M_{top} for each sub-sample**
- **Since they are statistically independent, take product of the sub-sample likelihoods** to combine into one result

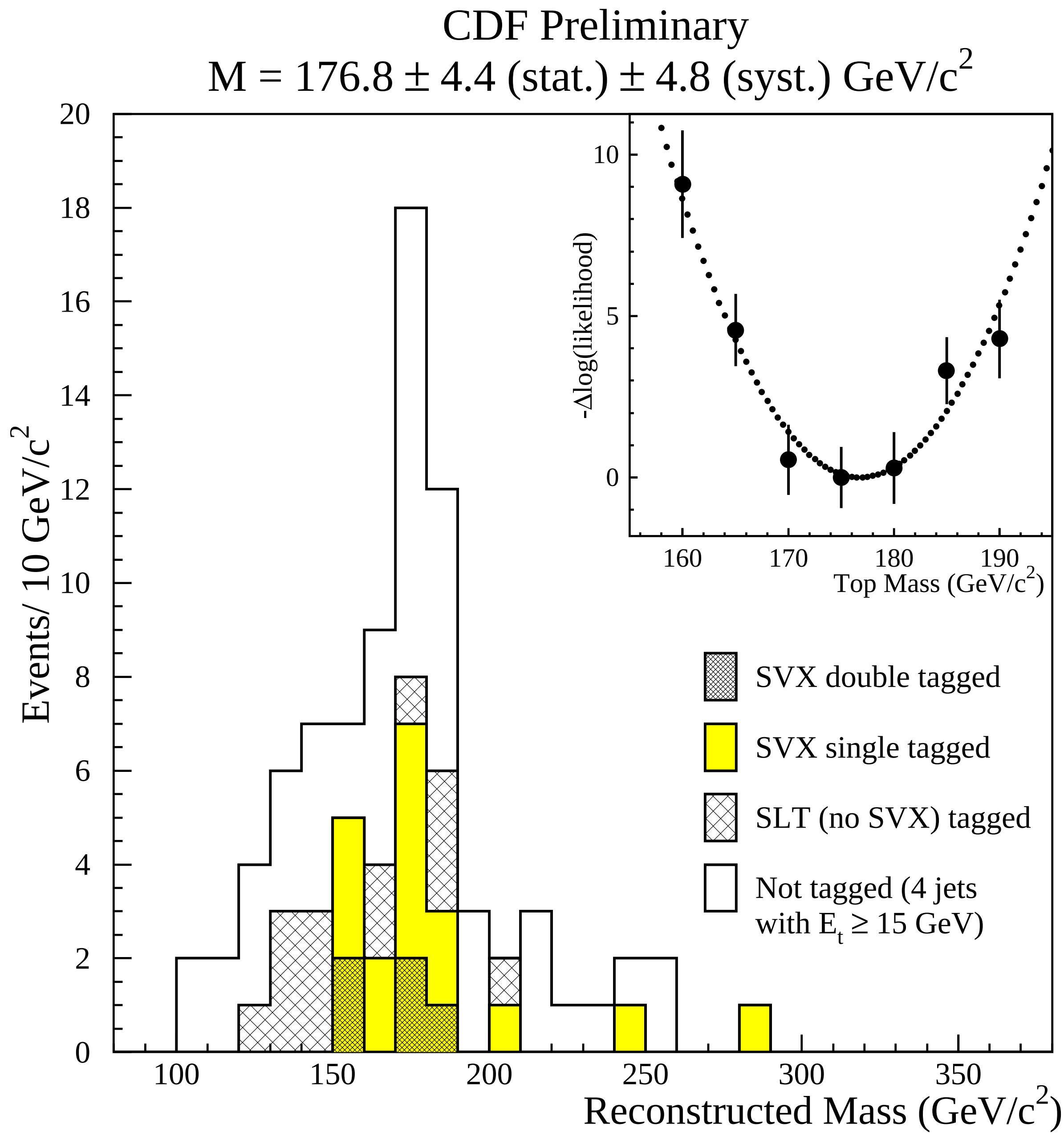
Results from the Optimized Method

CDF Preliminary

Subsample	Fitted Mass GeV/c^2	Stat. Uncertainty GeV/c^2
SVX or SLT tag (**Standard Method**)	175.6	5.7
No tag ($E_t > 15$)	180.9	6.4
SVX single tag	176.3	8.2
SVX double tag	174.3	7.9
SLT tag (No SVX)	140.0	24.1
Optimized	**176.8**	**4.4**

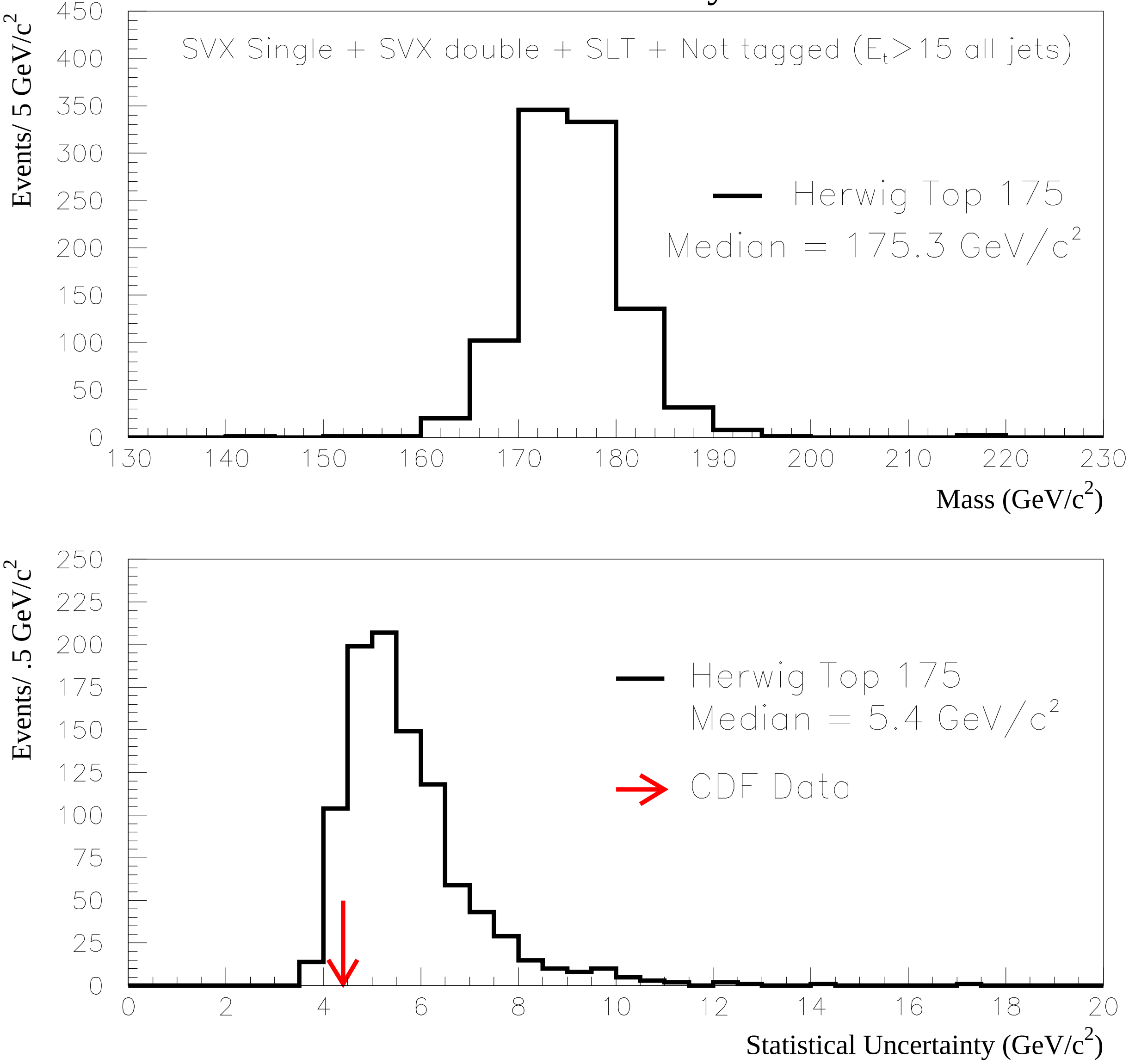
CDF Preliminary





CDF Preliminary
M = 176.8 ± 4.4 (stat.) ± 4.8 (syst.) GeV/c2
Events/ 10 GeV/c2
Reconstructed Mass (GeV/c2)
-Δlog(likelihood)
Top Mass (GeV/c2)
SVX double tagged
SVX single tagged
SLT (no SVX) tagged
Not tagged (4 jets with Et ≥ 15 GeV)

CDF Preliminary



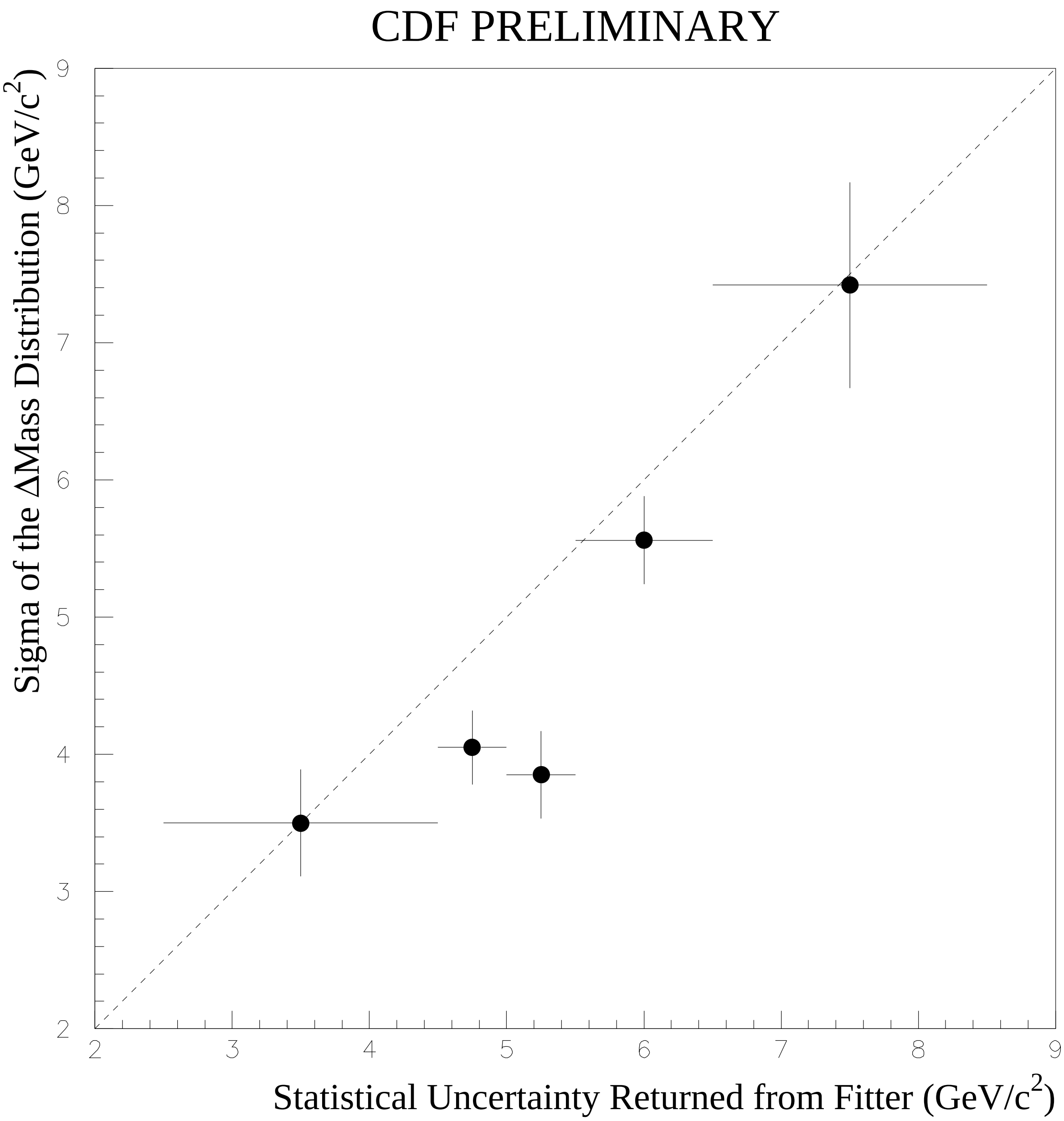
CDF Preliminary

Systematic Uncertainties for the Optimized Method

Systematic	Value GeV/c^2
Soft Gluon + Jet E_T Scale	3.6
Different Generators	1.4
Hard Gluon Effects	2.2
Kinematic and Likelihood Fitting Methods	1.5
b-tagging Bias	0.4
Background Spectrum	0.7
Monte Carlo Statistics	0.8
Total	4.8

Outrageous Fortune

- The statistical uncertainty returned by the fit is 4.4 GeV/c^2
- A study using our analysis technique on Monte Carlo data samples shows that the probability of observing a statistical uncertainty of 4.4 GeV/c^2 or less is 8.2%.
- These studies further show that when a small statistical uncertainty is returned by the method, the deviation from the true top mass is correspondingly small.
- If the rate of hard radiation in these Monte Carlo samples is reduced, this probability increases to 15%
- When the background is not constrained in the data fit, the fit returns less background. If in the Monte Carlo samples these lower background rates are used, the probability becomes 39%.


CDF PRELIMINARY
Sigma of the ΔMass Distribution (GeV/c²)
Statistical Uncertainty Returned from Fitter (GeV/c²)
2
3
4
5
6
7
8
9

Combining CDF and D0 Top Mass Measurements

- Used only Lepton+Jet Mass Measurements
  - CDF: $176.8 \pm 4.4 \pm 4.8$ GeV/c^2
  - D0: $169 \pm 8 \pm 8$ GeV/c^2
- Assumptions:
  - Made the conservative assumption that all the systematic errors, except energy scale, b-tagging bias and Monte Carlo statistics, are 100% correlated.
  - Found the central value by weighting by the statistical error only.
- Results:

$$M_{top} = 175.0 \pm 3.9 \pm 4.5 \text{ GeV/c}^2$$

$$\mathbf{M_{top} = 175 \pm 6 \text{ GeV/c}^2}$$

Summary of other $\mathrm{M_{top}}$ Measurements

CDF: Using Jet Charge and Jet Tagging Probability In Lepton+Jet Events

The L^{**} Method

- Add two terms to the event-fit χ^2:
- Use an SVX tagging Probability
- Assign a probability for each jet to be inconsistent $\rightarrow$ consistent with coming from the primary vertex
- Use this information to weight each combination of jet-to-parton assignments:
  - require jets used as b's to appear b-like
  - require jets used as W daughters to appear prompt
- Use an algorithm that estimates the leading quark charge ("jet-charge" algorithm) to discriminate b from $\bar{b}$ jets
- Including these data in the χ^2, choose best χ^2 combination

Result:

$$M_{top} \;=\; 174.2 \;\pm\; 5.5(stat) \pm 5.3(sys)\;\; GeV/c^2$$

D0 Dilepton Top Mass

- Because of the second neutrino, event fit is under constrained
- If one assumes a value for M_{top}, it is 0-C
- The kinematics of the event can be calculated (within a 4-fold ambiguity in neutrino momenta).
- Not all solutions are equally likely:
  - Assign weights based on Monte Carlo
  - Look at weights vs. Top mass for each event to extract a top mass
- D0 has two methods for determining the weights, results agree.

Result, using 3 $e\mu$ events only:

$$M_{top} \; = \; 158 \; \pm \; 24.0(stat) \pm 10(sys) \; GeV/c^2$$

CDF Dilepton Top Mass

Two Analyses:

- Compare the E_T of found jets to Monte Carlo templates from different masses.

Result:

$$M_{top} = 159^{+24}_{-22} \pm 17 \; GeV/c^2$$

Second Analysis:

One can derive the approximate expression:

$$M_{top}^2 \;=\; M_W^2 \;+\; 2\frac{< M_{lb}^2 >}{1- < cos(\theta_{lb}) >}$$

where, $< \mathbf{M_{lb}^2} >$ is the mean invariant mass of the lepton-b pair and $< \mathbf{cos}(\theta_{\mathbf{lb}}) >$ is the mean angle between the lepton and b in the W rest frame.

- Estimate $< \mathbf{cos}(\theta_{\mathbf{lb}}) >$ from Monte Carlo
- Use correspondence function between M_{top}^{raw} and M_{top}^{true}

Result:

$$M_{top} \;=\; 162 \;\pm\; 21.0(stat)^{+7.1}_{-7.6}(sys) \; GeV/c^2$$

CDF All Hadronic Top Mass

Same requirements as cross section analysis except also require:

- $N_{jet} \geq 6$ (and $N_{jet} \leq 9$)
- $\Sigma\, E_t > 200\ GeV/c^2$

With one or more SVX b-tags

- **Observe 142 tagged events on a calculated background of 113.**
- **Excess agrees with rate expected from top.**
- Perform 3-C Event fit

Result:

$$M_{top} \ = \ 187 \ \pm \ 8(stat)^{+13}_{-12}(sys)\ GeV/c^2$$

Using the Double b-tagged Events

In top mass determination, events with two b-tagged jets have advantages:

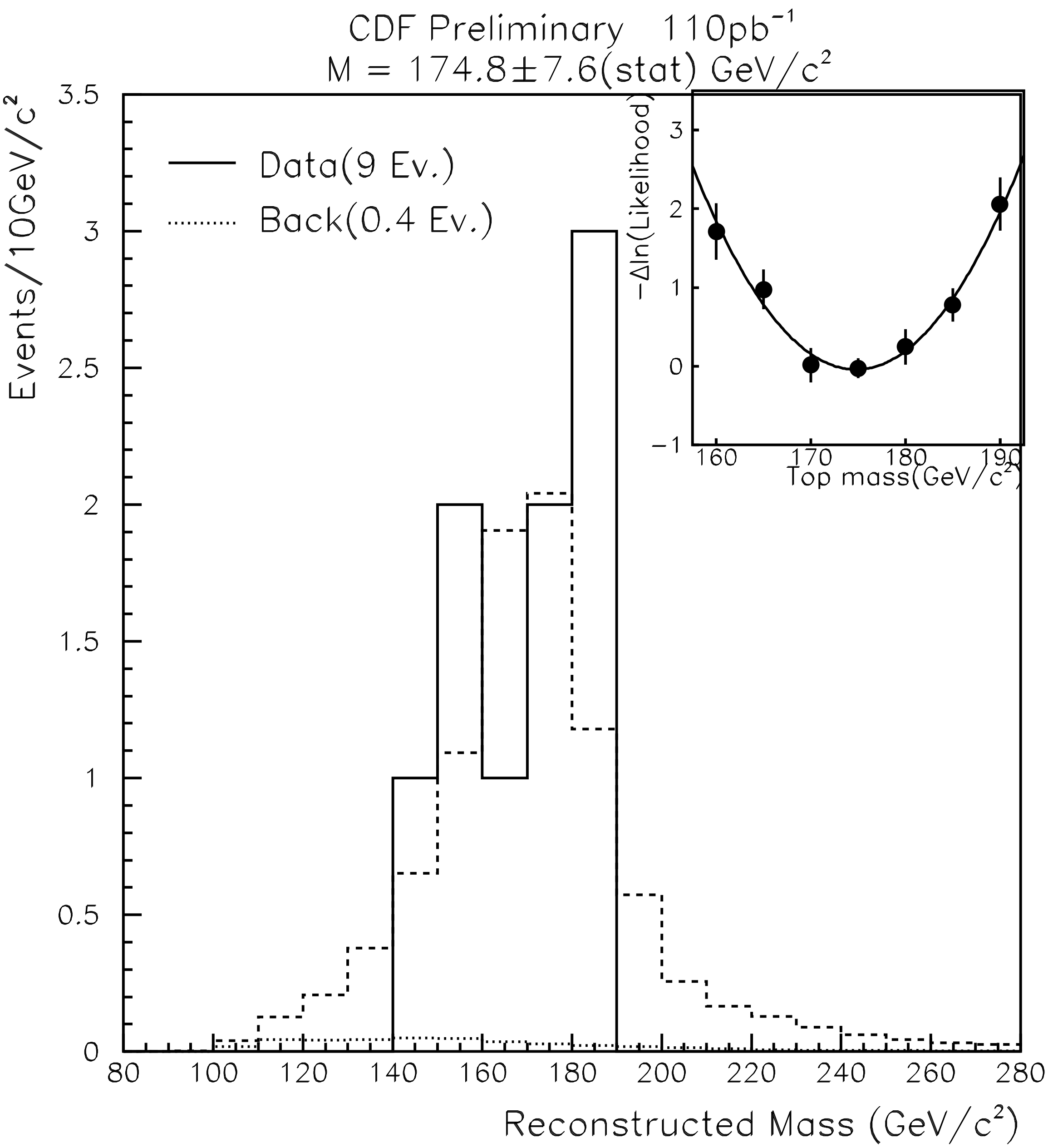
- The number of possible combinations per event is decreased from 12 to 4. $\Rightarrow$ choose correct assignment more often $\Rightarrow$ **better resolution on** M_{top}.
- Better Signal-to-Background
- Some systematic uncertainties are also smaller ($i.e.$ effect of hard gluon radiation)
- Use Loose b-tagging algorithm to increase statistics
- The two untagged jets must be the W. Can reject 2/3 of background by requiring $60 > M_{JJ} > 100\ GeV$, then constrain $M_{JJ} = M_W$.

We observe 9 events with an estimated background of 0.4 ± 0.1.

Results:

$$M_{top} = 174.8 \pm 7.6(stat) \pm 5.6(sys)\ GeV/c^2$$

This result is not statistically independent of the Standard Mass Analysis.


CDF Preliminary 110pb^{-1}
M = 174.8±7.6(stat) GeV/c^2
Events/10GeV/c^2
Data(9 Ev.)
Back(0.4 Ev.)
Reconstructed Mass (GeV/c^2)
−Δln(Likelihood)
Top mass(GeV/c^2)

Systematic uncertainties in top mass measurement on 2 b-tagged W+$\geq$4jet events

CDF Preliminary 110pb^{-1}

Systematic Uncertainties	values	
	(GeV/c^2)	(%)
Jet E_T Scale	2.9	1.7
Soft Gluon Effects	1.7	1.0
Different Generators	0.9	0.5
Hard Gluon Effects	3.6	2.1
Fit Configuration	0.9	0.5
Tagging Bias	2.0	1.1
Background Spectrum	0.1	<0.1
Likelihood method	0.6	0.3
Monte Carlo statistics	1.0	0.6
Total	5.6	3.2

1

Using Anti-tags and Jet charge:

The L^{**} Method

In an attempt to make optimal use of information in the lepton + Jets sample, we add two terms to the event fit χ^2:

- Use an SVX tagging Probability variable ($0 \rightarrow 1.$) for each jet
- weight each jet as inconsistent $\rightarrow$ consistent with coming from the primary vertex.
- Use this information to weight each combination of jet-to-parton assignments:
  - require jets used as b's to appear b-like
  - require jets used as W daughters to appear prompt
- Use an algorithm that estimates the leading quark charge ("jet-charge" algorithm) to discriminate b from $\bar{b}$ jets
- Including these data in the χ^2, choose best χ^2 combination
- Background estimate decreases from 6.3 to 4.1 events
- **This method increases the number of correct combinations in Monte Carlo top samples from $\sim$ 36% to $\sim$ 42 %**

Lost Information: Events with no SVX information are not used.

CDF Mass Determination Using the Dilepton Sample

Two Analyses:

- Compare the E_T of found jets to Monte Carlo templates from different masses.
  - Simple but not an optimal use of the information
  - Yields

$$M_{top} = 159^{+24}_{-22} \pm 17 \; GeV/c^2$$

- **New analysis makes more optimal use of the information in the event:**
  - In the W rest frame, ignoring lepton masses:

$$M_{top}^2 \;=\; M_W^2 \;+\; M_b^2 + 2 M_W E_b, \qquad E_\nu \;=\; E_l \;=\; \frac{M_W}{2}$$

  - E_b in this frame yields a measure of M_{top}
  - By forming the invariant M_{lb}^2:

$$M_{lb}^2 \;=\; M_l^2 \;+\; M_b^2 + 2 E_l E_b \;-\; 2 P_l P_b cos(\theta_{lb})$$

  - since E_l and P_l are $\frac{M_w}{2}$ we get

$$\frac{M_{lb}^2 - M_b^2}{M_w} \;=\; E_b \;-\; P_b cos(\theta_{lb})$$

- **Only M_{lb}^2 and $cos(\theta_{lb})$ vary event-by-event**
- for an average over all events, assuming $E_b \approx P_b$ we get:

$$M_{top}^2 \;=\; M_W^2 \;+\; 2\frac{< M_{lb}^2 >}{1- < cos(\theta_{lb}) >}$$

- measure $< M_{lb}^2 >$ and estimate $< cos(\theta_{lb}) >$ from Monte Carlo.
- Use $< cos(\theta_{lb}) >= 0.118$
- Create a correspondence function that translates from M_{top}^{raw} to M_{top}^{true}

Results:

$$M_{top} \;=\; 162 \;\pm\; 21.0(stat)^{+7.1}_{-7.6}(sys)\; GeV/c^2$$

D0 Mass Determination using the Dilepton Sample

- Same event selection as the D0 cross section analysis
- 5 events (3 $e\mu$) with a background estimate of 1.7± 0.5

Perform an Event Fit:

- Assume a top mass, loop over all masses
- Define a likelihood for each top mass, weighting each solution
- Take peak in likelihood as an estimate of the top mass for each event
- Extract final top mass with maximum likelihood fit
- Weights are determined by two methods, agreement between the two methods is good

Result, using 3 $e\mu$ events only:

$$M_{top} \ = \ 158 \ \pm \ 24.0(stat) \pm 10(sys) \ GeV/c^2$$

CDF Mass Determination using the All Hadronic Decay Mode

Using the same sample used for the all hadronic cross section, except

- Require $N_{jet} \geq 6$ (and $N_{jet} \leq 9$)
- Lower $\Sigma\, E_t$ requirement from 300 to 200 GeV/c^2

With one or more SVX b-tags,

- **Observe 142 tagged events on a calculated background of 113.**
- **Excess agrees with rate expected from top.**

CDF Measurement of V_{tb}

- Unitarity within a three-generation Standard Model implies $V_{tb} \sim 1.0$
- Two CDF analyses for V_{tb}, both use $l + jets$ and dilepton samples:
  - Measure the ratio of events with 0, 1, and 2 b-tags
  - Use this to extract

$$b = \frac{Br(t \to Wb)}{Br(t \to WX)}$$

- By comparing ratios of these event yields, this result is independent of the value of $\sigma_{t\bar{t}}$ and $\frac{Br(W \to l\nu)}{Br(W \to q\bar{q})}$

Results of a maximum likelihood Combining all Information

$$\mathbf{b} \;=\; \frac{\mathbf{Br(t \to Wb)}}{\mathbf{Br(t \to WX)}} \;=\; \mathbf{0.94 \pm 0.27(stat)} \;\; \mathbf{\pm 0.13(syst)}$$

$$\mathbf{b} \;\; > \mathbf{0.34 \;\; at \;\; 95\% \;\; c.l.}$$

In a three-generation Standard Model,

$$b \;=\; \frac{|V_{tb}|^2}{|V_{td}|^2 \;+\; |V_{ts}|^2 \;+\; |V_{tb}|^2}$$

Assuming 3-generation unitarity this yields:

$$|\mathbf{V_{tb}}| \;=\; \mathbf{0.97 \;\pm\; 0.15 \;\pm\; 0.07}$$

and

$$|\mathbf{V_{tb}}| \;\; > \mathbf{0.58 \;\; at \;\; 95\% \;\; c.l.}$$

Conclusions

Top has been observed and $\sigma_{t\bar{t}}$ has been measured in many decay modes:

$$\mathbf{t\bar{t} \rightarrow W + Jets + X}$$
$$\mathbf{t\bar{t} \rightarrow W + b + Jets + X}$$
$$\mathbf{t\bar{t} \rightarrow l^+ l^- + Jets + X}$$
$$\mathbf{t\bar{t} \rightarrow l^+ + \tau + Jets + X}$$
$$\mathbf{t\bar{t} \rightarrow 6\ Jets + X}$$

- **These results agree within statistics but the measurement uncertainties are large ($\sim 30 - 100\%$).**

- World Average Top Cross Section at 175 GeV/c^2:

$$\sigma_{\mathbf{t\bar{t}}} \;=\; \mathbf{6.4^{+1.3}_{-1.2}\ pb}$$

- QCD predictions range from 4.7 to 5.6 pb

- New Top mass results emphasize optimal use of information and are much more precise:

$$M_{Top} = 169 \ \pm 11 \ GeV/c^2 \qquad D0 \quad L + jets$$

- **Decrease in total uncertainty from 18 to 11 GeV/$\mathbf{c^2}$**

$$M_{Top} = 176.8 \ \pm 6.5 \ GeV/c^2 \qquad CDF \quad L + jets$$

- **Decrease in total uncertainty from 9.1 to 6.5 GeV/$\mathbf{c^2}$**
- Combined Average:

$$M_{Top} = 175 \ \pm 6 \ GeV/c^2 \qquad CDF/D0 \quad L + jets$$

- in an explicit study of top decay branching ratios:

$$\mathbf{b} \ = \ \frac{\mathbf{Br(t \rightarrow Wb)}}{\mathbf{Br(t \rightarrow WX)}} \ = \ \mathbf{0.94 \pm 0.27(stat) \ \pm 0.13(syst)}$$

$$\mathbf{b} \ > \mathbf{0.34 \ at \ 95\% \ c.l.}$$

Nothing observed in top production or decay is glaringly inconsistent with the Standard Model.